Performance assessment of an LCPV/T solar hybrid plant for a wellness center building in Mexico

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Abstract

Buildings are responsible for almost half of the worldwide final energy consumption. A large amount of this energy is produced by fossil fuels. Solar energy can effectively produce the thermal and electric energy consumed by buildings, using hybrid photovoltaic/thermal (PV/T) technologies. This document presents a performance evaluation of a hybrid low concentrating PV/T (LCPV/T) plant operating in a student health and wellness center building on a college campus in Mexico. The hybrid solar plant consists of 144 parabolic trough-based collectors with a hybridized receptor that includes c-Si PV cells. The results showed that the solar field could cover up to 91% of the hot water demand of the building during the summer season and 32% during the winter period. The peak thermal and electric power were 190 kW and 37.6 kW, respectively. The hybrid system could annually save USD 7,185, accounting for heat (natural gas boiler), and electricity generation. Nevertheless, the payback period was 17.37 years, which was mainly caused by a reduced natural gas price in Monterrey, Mexico. Finally, an annual reduction of 97.9 metric tons of CO_2 emissions was reached.

Keywords: Solar energy, hybrid collectors, LCPV/T, dynamic evaluation, buildings, Mexico.

1. Introduction

In 2018, about 55% of the world's population lived in urban areas. This portion is projected to grow to 68% by 2050 (United Nations, 2019). Most of these people will probably allocate in buildings due to urban development and land limitations in most of the cities. Buildings are responsible for almost half of the worldwide final energy consumption, which is mainly produced by fossil fuels. Solar energy is a vast and renewable primary energy source that can effectively and efficiently produce the electrical and thermal energy consumed by buildings. Hybrid solar photovoltaic/thermal (PV/T) collectors can produce thermal and electrical energy simultaneously, reducing the area required for installation in comparison with stand-alone photovoltaics and thermal collectors. This characteristic is particularly convenient for buildings due to limited roof available area and energy profiles consumption, both thermal and electrical.

There have been several studies regarding the performance evaluation of PV/T plants. For instance, Sotehi et al., 2016 developed a theoretical approach of a Net Zero Energy Building (NZEB) using hybrid PV/T solar collectors in Ouargla City. They found that is possible to cover the domestic hot water demands of the building with the hybrid technology coupled with passive solar architecture to reduce energy consumption. Moreover, the electricity produced could cover the annual needs for air conditioning, lighting, and household equipment. Fuentes et al., 2018 performed an experimental evaluation between hybrid PV/T and simple PV systems intended for Building Integrated PV (BIPV). They concluded that the PV/T system did not present higher electrical efficiencies than simple PV as expected due to the active cooling mechanism. However, the combined thermal and electrical efficiencies reached 80% and 19% for the exergy efficiency. Yang et al., 2019 simulated a low-concentrating PV/T triple-generation system for hot water, power, and cooling. The results showed that the hybrid system could generate hot water at 45°C - 90°C, with an electrical efficiency of the PV cells of 10%, and a COP above 0.5 for the lithium-bromide absorption chiller.

Herrando et al., 2019 performed an evaluation of a 1.68 MWp solar combined cooling, heating, and power (S-CCHP) system based on hybrid photovoltaic/thermal (PV/T) collectors for a University Campus in Bari, Italy. The hybrid plant can satisfy 20.9%, 55.1%, and 16.3% of the space-heating, cooling, and electrical demands of the campus. The techno-economic performance evaluation resulted in a 16.7 years payback time. Wang et al.,

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2019 developed a techno-economic assessment of hybrid PV/T systems and compared them with conventional solar-energy systems; PV and evacuated tubes collectors. They found that the PV/T system surpassed other conventional ones in terms of energy production, supplying with 82.3% and 51.3 % of the electric and thermal building demand, respectively. However, PV presented the lowest payback period (9.4 years) and the lowest levelized cost of energy (LCOE) of 0.089 €/kWh.

The literature review showed that most of the performance evaluations of PV/T plants for building applications have been performed mainly in Europe and Asia. Consequently, there is a lack of information and knowledge about the potential of this technology in Latin America, despite that most of the increase in energy consumption in buildings is expected to occur in emerging economies. Moreover, the levels of insolation that reach most of the Mexican territory, like Monterrey, increase the potential of using solar technologies to produce heat and power.

This document presents a dynamic performance evaluation of an LCPV/T plant for a student health and wellness center building in Monterrey, Mexico. The study is based on transient simulations developed in TRNSYS software. Thermal and electrical energy yields of the plant are evaluated, along with the other operational variables, such as thermal and electrical peak power, and temperature profiles. An economic evaluation of the solar hybrid plant in terms of estimating the final cost of the system, the annual savings due to fuel and electricity consumption reduction, and the payback time of the investment is also approached. Moreover, the environmental impact due to the displacement of Natural gas is evaluated in terms of CO_2 emissions.

2. Methodology

The evaluation of the LCPV/T plant was performed in the TRNSYS software environment. The hybrid plant consists of 144 hybrid collectors, 12 rows of 12 collectors each, that cover a total roof area of 1281 m^2. The hybrid collectors are based on a small-sized parabolic trough with a triangular receptor that has attached c-Si back-contact solar cells, on the sides of the receiver that collect concentrated sunlight. The hot water produced by the plant will be used to cover part of the thermal demands of the building; domestic hot water (DHW) and pool heating. While the electrical production is just considered to be additional energy input to the building electricity consumption, which will be accounted for monetary and environmental gains. A simplified process diagram of the simulated system is presented in Fig 1. Energy Plus Weather (EPW) files were used to simulate a typical meteorological year in the studied location.

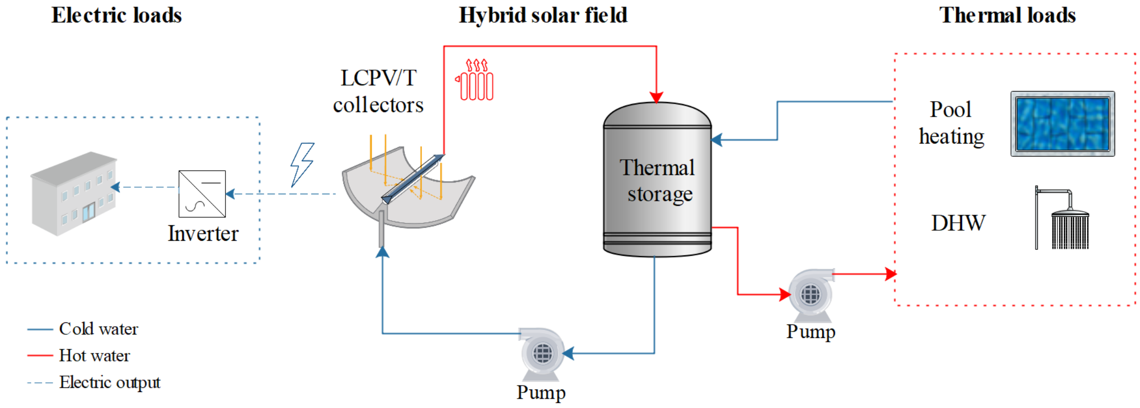

Fig. 1. Hybrid solar heat&power system configuration.

The hybrid collector was modeled using a modified version of Type 50f that considers the incidence angle modifier of the system. Type 50f is a component developed to model concentrating hybrid solar collectors where the thermal losses are a function of the wind velocity and collector temperature. As we proposed in this study, type 50f was modified to include the incidence angle modifier of the system $K(\theta)$ to model the concentrating collector. Moreover, the thermal performance parameters, such as the contact resistance between PV cells and absorber R_c, heat transfer coefficient between the duct and the heat transfer fluid $U_{Abs_{Fluid}}$, and the heat transfer coefficient for thermal losses of the collector U_L, were obtained using a one-dimensional steady-state model of the hybrid collector, previously developed by (Acosta P., 2016). The principal equations to calculate the thermal and electric performance of the hybrid LCPV/T collector are presented in eq.1– eq.6. The most important inputs of the simulation model are presented in Table 1.

Useful thermal output (Duffie and Beckman, 2013):

$$\dot{Q}_u = F_R A_a \left[S - \frac{A_r}{A_a} U_L (T_i - T_{amb}) \right] \quad \text{(eq. 1)}$$

Collector heat removal factor (Florschuetz, 1979):

$$F_R = \frac{\dot{m}\, cp}{U_L} \left[1 - \exp\left(-U_L F' / \dot{m}\, cp \right) \right] \quad \text{(eq. 2)}$$

Collector efficiency factor (Duffie and Beckman, 2013):

$$F' = \left(1 + \frac{U_L}{U_{Abs_{Fluid}}} \right) \quad \text{(eq. 3)}$$

Heat loss coefficient (Duffie and Beckman, 2013):

$$U_L = \frac{Q_{Loss}}{A_r (T_r - T_{amb})} \quad \text{(eq. 4)}$$

Incidence angle modifier (Gaul and Rabl, 1980):

$$K(\theta) = 1 - b_o \left(\frac{1}{cos(\theta)} - 1 \right) \quad \text{(eq. 5)}$$

Electric output (Florschuetz, 1979):

$$P_e = \frac{A_a\, S\, \eta_{PV}}{\alpha} \sqrt{\left\{ 1 - \frac{\eta_{PV_r}\, K_T}{\eta_{PV}} \left[F_R (T_i - T_a) + \frac{S}{U_L} (1 - F_R) \right] \right\}} \quad \text{(eq. 6)}$$

The parameter b_o, which shapes the curvature of the function presented in eq. 5, was taken from the value obtained by (Bernardo et al., 2011).

Table 1. Inputs of the simulation model in TRNSYS.

Feature	Value
Process and solar field	
Daily hot water demand	30 m^3
Temperature demand	55℃
Solar field azimuth	16.6
Thermal storage capacity	30 m^3
Heat demand	94.4 kW
Hybrid collector	
Optical efficiency, η_{0A}	0.601
Concentration ratio	14.8
Internal heat transfer coefficient, $U_{Abs_{Fluid}}$	3838 W/m^2K
Heat loss coefficient, U_L	2.77 W/m^2 K
Temperature coefficient, K_T	0.33 %/K
Energy prices	
Natural Gas	3.13 USD $/GJ
Electricity (average commercial tariff)	0.064 USD $/kWh

The annual heat and electricity production of the hybrid solar plant is calculated with the following relations:

Thermal energy yield:

$$Q_u = \int \dot{Q}_u dt \tag{eq. 7}$$

Electrical energy yield:

$$E_{el} = \int P_e dt \tag{eq. 8}$$

The annual monetary savings caused by onsite energy generation, both thermal (Q_u) and electrical (E_{el}), were calculated with eq. 9-14. For the thermal part, the calculation was based on obtaining how much fuel (F) is needed in order to produce the same amount of heat that the hybrid solar plant generates. The efficiency considered for the boiler was $\eta_b = 60\%$, which is the average efficiency of a low load natural gas boiler (IEA International Energy Agency, 2010). To determine the monetary savings (C_F) of the displacement of natural gas, the local price (FP) of Natural gas was considered, Table 1. For electricity generation savings (C_E), the average efficiency of a DC-AC conversion ($\eta_e = 95\%$) as well as a local tariff (EP) for commercial electricity service were considered to calculate the cost savings due to electricity generation (M_E). The total annual cost savings (C_s) is determined with eq. 14.

$$Q_F = \frac{Q_u}{\eta_b} \tag{eq. 9}$$

$$F = \frac{Q_F}{\left(C_{LHV_f}\right)} \tag{eq. 10}$$

$$E = E_{el} \cdot \eta_e \tag{eq. 11}$$

$$C_F = FP \cdot Q_F \tag{eq. 12}$$

$$C_E = EP \cdot E \tag{eq. 13}$$

$$C_s = C_F + C_E - C_{O\&M} \tag{eq. 14}$$

The CO_2e emissions abatement potential is estimated using the emissions factors for natural gas boiler combustion and electricity generation determined by the Intergovernmental Panel on Climate Change (IPCC) in 2006. For Natural gas combustion, the emissions factor is 0.2 kgCO_2e/kWh, whilst for electricity generation the emissions factor is 0.45 kgCO_2e/kWh.

The total hybrid plant cost (C_o) was estimated from eq. 15 (Kalogirou, 2009), considering the cost breakdown presented in Table 2, and the payback time (PBT) of the plant was calculated considering an average inflation rate (i_F) of 10%, a local discount rate (d) of 5%, and an annual energy production derate of 0.5%. The cash flow for each year are calculated independently for the fuel and electricity cost savings and taking into account the time value of money.

$$PBT = \frac{ln\left[\frac{C_o(i_F - d)}{C_s} + 1\right]}{ln\left(\frac{1 + i_F}{1 + d}\right)} \tag{eq. 15}$$

Table 2. Cost breakdown of the LCPV/T plant.

Component	Cost
Parabolic trough collectors, USD	$209.7 \cdot A_{LCPVT}$
Hybrid receiver, USD	$0.2 \cdot C_{LCPVT}$
Water tank, USD (Wang et al., 2020)	$0.874 \cdot V_T(l) + 763.5$

Inverter, USD/kW	200
Pump, USD (Wang et al., 2020)	$500(P_{pump}/300)^{0.25}$
Piping*, USD (Wang et al., 2020)	$(0.897 + 0.21D_{pipe}) \cdot L_{pipe}$
Controller, USD	600
Installation cost, USD (Wang et al., 2020)	$0.2 \cdot$ Total component cost
Annual O&M cost, USD (Wang et al., 2020)	$0.005 \cdot$ Total component cost

* D_{pipe} in [mm] and L_{pipe} in [m]

3. Results

The monthly thermal and electric yield and the solar fraction of the hybrid LCPV/T plant are presented in **Fig. 2**. It could be noticed that the proposed solar plant can achieve a solar fraction as high as 91% during the summer season. Conversely, during winter the hybrid plant supplied 32% of the building's hot water demand. Q load represents the total hot water demand for a specified period of time (monthly, annually). Q useful is the thermal energy produced by the hybrid solar plant that can be consumed by the building. Q aux is the heat produced by a natural gas-fired boiler to cover the total hot water demand of the building. E useful is the electricity produced by the hybrid plant. **Fig. 3** presents the energy yield of the solar field on an annual basis. The hybrid plant produced 55% of the annual hot water demand of the studied building. Moreover, an additional 45.7 MWh of electricity is produced. This represents an important gain that will reduce the grid electricity consumption of the building, hence produce additional monetary savings and CO_2e emissions abatement.

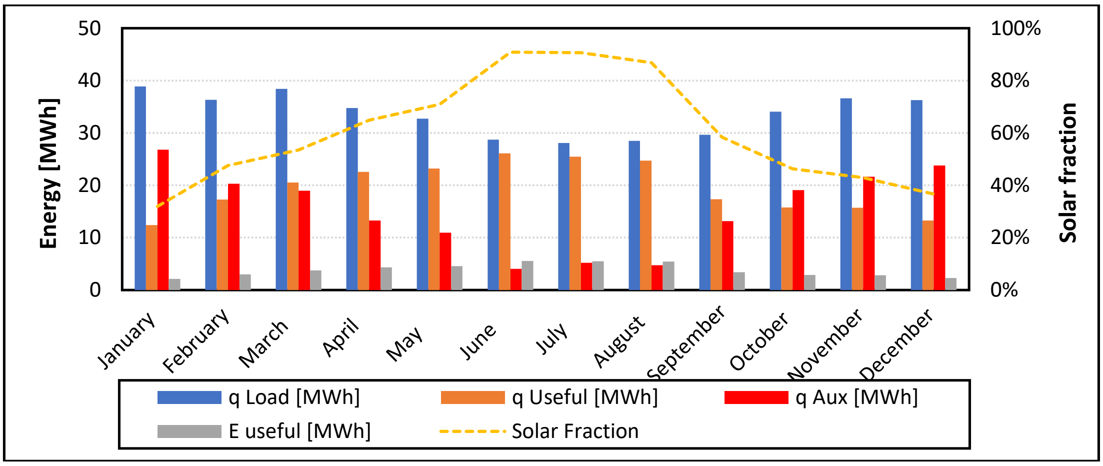

Fig. 2: Solar hybrid plant monthly energy yield and solar fraction.

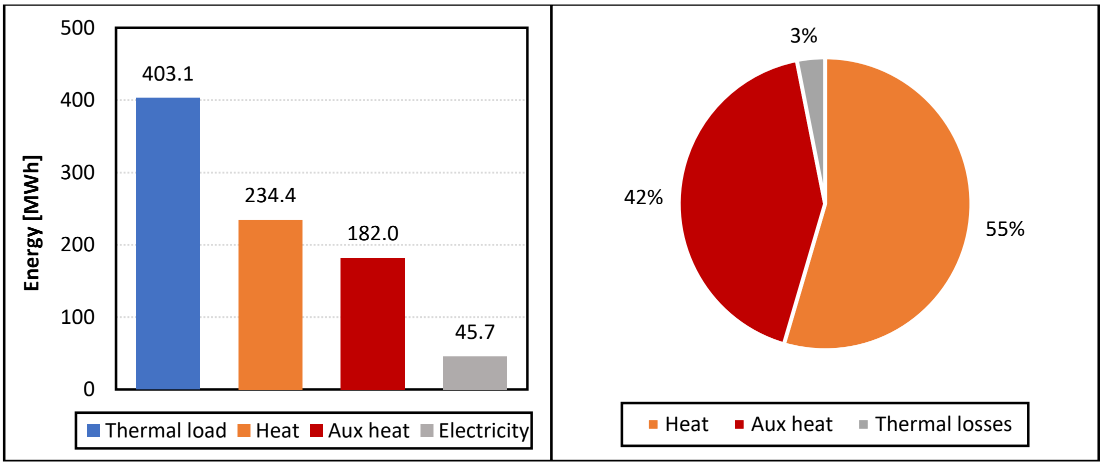

Fig. 3: Annual energy yield (left), and share of hot water demand (right).

Regarding the hot water temperature produced by the solar hybrid field considering a constant heat demand of 94.4kW, during summer the maximum recorded water outlet temperature was 60℃, while in winter was 40℃,

Fig. 4. The peak values for the thermal and electrical power, during a typical summer day, were 190 kW and 37.6 kW, respectively, **Fig. 5**.

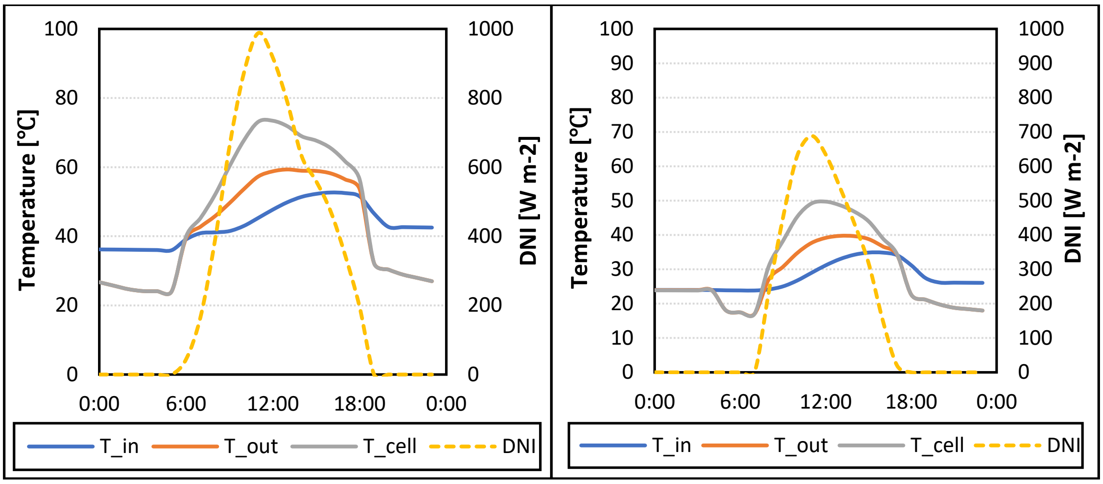

Fig. 4: Temperature profile and DNI during summer (left), and winter (right) typical days.

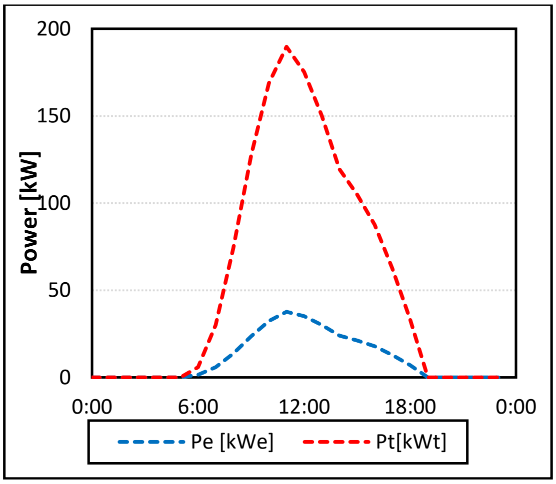

Fig. 5: Thermal and electrical peak power during a summer typical day.

The monetary and environmental benefits of the clean energy production of the hybrid solar plant are presented in **Fig. 6**. It could be noticed that the hybrid plant can annually generate USD 7,185 of monetary savings, accounting for heat and electricity generation. Moreover, the annual reduction of CO_2e emissions can reach 97.9 metric tons, of which the majority, i.e., 80% (78.14 tons) is associated with the displacement of natural gas for heat generation. This is equivalent to take out of the streets nearly 21 passenger vehicles every year (United States Environmental Protection Agency, 2020). If we consider a 25 years lifespan of the hybrid plant, its application into the wellness center can avoid the emission of 2,446 metric tons of CO_2e. The total initial cost of the hybrid plant is estimated to be $178,657 USD, and the payback period obtained is 17.37 years. The electricity price to natural gas price ratio obtained is 5.68, which clearly shows a remarkably low price of natural gas, despite the electricity tariff is also lower in comparison with other regions. This price ratio is 16.4% greater than the highest reported by (Wang et al., 2020), which was 4.88 (Italy). Better economic performance of hybrid plants is achieved when the energetics price ratio is closer than one.

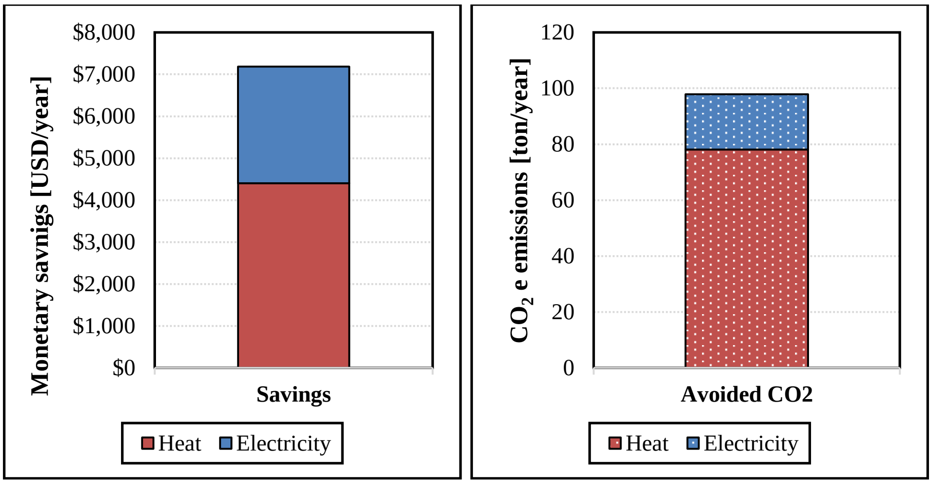

Fig. 6: Annual monetary savings (left) and avoided CO_2 emissions (right).

4. Discussion

The performance of a solar hybrid plant in a student health and wellness center building on a university college in Monterrey was studied. Results show that the thermal demand, by means of domestic hot water and pool heating, can be partially covered by the proposed solar hybrid system. During the summer season, the solar fraction can achieve values of up to 91%, which is possible due to the increased solar resource available, and the reduced thermal losses caused by higher ambient temperature during this season. On the other hand, during winter, only 32% of thermal demand is covered by the solar hybrid plant, due to lower available insolation and ambient temperatures.

The thermal storage capacity allows that the solar field water outlet temperatures remain relatively low, even during high solar resource days. This is particularly important to keep the temperature of the hybrid collectors low enough to preserve electricity production. The physics of LCPV/T collectors, like the one evaluated in this document, provokes that the electric and thermal systems of the collector are thermally-coupled, which means that an increase in the receptor temperature will result in a temperature rise in the PV module attached to the hybrid receptor, hence a reduction in solar to electricity conversion. Another relevant operational characteristic that helps maintaining the temperature of the hybrid receptor under acceptable ranges is a constant hot water demand, which is common in wellness center buildings were the hot water demand is relatively constant throughout the year, due to the consumption of hot water for pool heating, showers, and faucets.

Regarding the economic analysis, it could be noticed that the hybrid plant system is a costly alternative for heat and power generation, that offers a payback time of nearly 17 years, which is long in comparison with other clean energy generation systems that may present payback periods between 3-8 years. The long payback period is mainly caused by the low local price of natural gas in Monterrey, and with a lower outcome, by the subsidized electrical commercial tariff scheme in Mexico. The price ratio of electricity and natural gas should be lower (<2.0) in order to achieve greater monetary savings. Further efforts should be made in order to reduce the total component and installation cost of the proposed hybrid technology in order to achieve more competitive costs in comparison with conventional technologies. Moreover, higher fuel prices and local incentives would make the proposed technology more attractive for investment. It is important to mention that if the economic performance of the proposed plant is not the decision-maker, from the environmental perspective, hybrid solar technology has an excellent CO_2 emission reduction potential, achieving, in this case, a specific reduction of 76.4 $kgCO_2e$ per square meter of the required installation area. Both the economic and environmental impact of the proposed hybrid plant can have a more significant effect when the thermal generation displaces other fuels like Diesel, Fuel Oil, or LPG.

5. Acknowledgments

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